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AUTONOMY METRICS

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ABSTRACT. JPL missions currently being designed and developed are counting on increased spacecraft autonomy to achieve low cost operations goals and to allow support of fleets of planetary spacecraft with limited Deep Space Network (DSN) resources. This paper presents four metrics that quantitatively define spacecraft autonomy and which will be used at JPL to:

- set measurable autonomy goals for future missions,
- evaluate and compare benefits between competing automation technology candidates, and
- compare autonomy across missions

The four autonomy metrics measure the degree to which spacecraft and mission designs permit:

- longer periods of no-track
- shorter periods of track
- less communication between flight and ground
- less total ops workforce

The results of a survey applying these metrics to historic missions (including Voyager, Galileo, Ulysses, and Topex) and planned future missions (including New Millennium, Pluto Express, and Stardust) are charted, showing rather startling differences between autonomy achieved by missions that have already flown vs. autonomy predicted by some missions that have yet to fly. Several orders of magnitude autonomy increases are being projected.

1. INTRODUCTION: SPACECRAFT AUTOMATION VS. SPACECRAFT AUTONOMY

There are many good, competing ideas of what spacecraft automation "really" is. One definition is that a spacecraft which executes a pre-planned sequence without human intervention has demonstrated automation. A second definition is that spacecraft automation extends beyond executing pre-programmed sequences and includes the ability of the spacecraft to react to unplanned events through event driven rules. A third definition of spacecraft automation is that the spacecraft reacts to unplanned events not just by executing pre-programmed rules, but by on-board intelligent agent software or inference engine generated commands, again without human intervention.

An example of the first type of spacecraft automation are the two JPL Voyager spacecraft both of which demonstrated the ability to execute pre-programmed planetary flyby sequences without ground intervention. The Voyager spacecraft also demonstrated examples of the second type of rule-based automation: on-board fault protection algorithms which allowed both spacecraft to respond to unplanned hardware faults by switching to backup, redundant systems without the ground being involved. The NASA New Millennium Flight plans to fly on-board intelligent agent software and demonstrate the third type of spacecraft automation.

All of these examples of spacecraft automation can be mission enhancing, or even mission enabling. <u>These automation examples may or may not result in lower operations and DSN tracking costs</u>. Sequences which the s/c can execute without ground intervention may require an enormous ground workforce to plan, model, implement, constraint check, simulate, uplink, etc. and be much more expensive than a set of commands that are uplinked in a joystick mode by a small ops staff. On-board fault protection rules that require large teams to analyze and to recover deterministic control of the spacecraft after they trigger, may drive ops and tracking costs up enormously. The ops staffing costs to support the programming, performance analysis, and trouble-shooting of on-board intelligent agents, are not well understood.

The metrics proposed in this paper do try and consider DSN tracking and operations cost. They are called autonomy metrics and try to reflect the degree to which the ground can "ignore" a spacecraft and leave it on its own. Spacecraft autonomy can be enhanced by spacecraft designs which provide a variety of attributes including flight margins, decoupled (non-interactive) subsystem behavior, minimum flight rules and constraints, and sometimes, on-board automation.

2. FOUR PROPOSED SPACECRAFT AUTONOMY METRICS

Below are functional definitions for four metrics that try and reflect the degree of spacecraft autonomy

$$\text{SPACECRAFT CONTROL AUTONOMY} = \frac{\text{no track duration}}{\text{size of cmd uplink} \times \text{workforce to prepare s/c uplink}} \times \frac{\text{no-track duration}}{\text{track duration}}$$

$$\text{SPACECRAFT ENGINEERING ANALYSIS AUTONOMY} = \frac{\text{no track duration}}{\text{size of eng downlink} \times \text{workforce to analyze eng downlink}} \times \frac{\text{no-track duration}}{\text{track duration}}$$

$$\text{SPACECRAFT SCIENCE ANALYSIS AUTONOMY} = \frac{\text{no track duration}}{\text{size of sci downlink} \times \text{workforce to analyze sci downlink}} \times \frac{\text{no-track duration}}{\text{track duration}}$$

$$\text{SPACECRAFT MARGIN MANAGEMENT AUTONOMY} = \frac{1}{\text{number of s/c margins \& consumables managed on ground} \times \text{workforce required to manage s/c margins \& consumables}}$$

3. SPACECRAFT CONTROL AUTONOMY

Spacecraft Control Autonomy is associated with the duration that the s/c routinely goes unattended, without commanding (and without any ops contact or DSN tracking). Control autonomy is inversely associated with the number of commands that must be routinely uplinked (when the s/c is tracked) and with the size of the ops workforce that it takes to plan, prepare, and transmit the commands. It is scaled by the ratio of average no-track to track duration, to discourage small increases in no-track duration which result in large increases in track duration.

Spacecraft Control Autonomy can be improved by designing a spacecraft or mission that requires less frequent ground commanding. The metric indicates that a spacecraft that uses a higher-order command language that results in a smaller command uplink, is more autonomous. It indicates that a spacecraft that is designed in such a way as to require only a small ops team workforce to provide command and control, has high autonomy. Finally, it indicates that adding on-board command automation that may increases no-track duration, has to be weighed by it's effect on ops workforce, if Spacecraft Control Autonomy is to be maximized.

It's worth mentioning that Spacecraft Control Autonomy can be artificially improved by bookkeeping ground ops workforce doing planning & command against some other task. To discourage this, rules for using these autonomy metrics require that the four workforce estimates used in the four metrics, sum up to total ops workforce. The result is that artificially improving one autonomy metric by fiddling its workforce, will end up degrading one or more of the other autonomy metrics.

4. SPACECRAFT ENGINEERING ANALYSIS AUTONOMY

Spacecraft Engineering Analysis Autonomy is associated with the duration that the s/c routinely goes unattended, without the need for the ground to collect and analyze engineering data (and without any ops contact or DSN tracking). Engineering analysis autonomy is inversely associated with the number of bits of engineering data that must be routinely downlinked (when the s/c is tracked) and with the size of the ops workforce that it takes to process and analyze the data and run whatever performance and trend models that are required for spacecraft operation. This autonomy metric is also scaled by the ratio of average no-track to track duration, to discourage small increases in no-track duration which result in large increases in track duration.

Spacecraft Engineering Analysis Autonomy can be improved by designing a spacecraft or mission that requires less frequent ground collection and analysis of spacecraft engineering data. The metric indicates that a spacecraft that uses on-board data monitoring and downlink data compression or summarization that results in a smaller engineering downlink, is more autonomous. It indicates that a spacecraft that is designed in such a way as to require only a small ops team workforce to provide performance analysis, has high autonomy. Finally, it indicates that adding on-board data monitoring automation that may increases no-track duration, has to be weighed by it's effect on ops workforce, if Spacecraft Engineering Analysis Autonomy is to be maximized.

5. SPACECRAFT SCIENCE ANALYSIS AUTONOMY

Spacecraft Science Analysis Autonomy is associated with the duration that the s/c routinely goes unattended, without the need for the ground to collect and analyze science data (and without any ops contact or DSN tracking) and inversely with the size of the ops workforce required to capture, analyze, archive, and otherwise deal with the science data downlinked. For the of this metric, science analysis i defined loosely to include only science operational analysis, the analysis that must 1) completed routinely to support on-going operational planning and sequence design

The above parameters above seem intuitively right to associate with science analysis autonomy. The parameter that seems to cause the most discomfort in the four autonomy metrics is that Spacecraft Science Analysis Autonomy is defined to be inversely proportional to the amount of science data downlinked. This is because the metrics are intended to address autonomy, not science value. What this says is that all things being equal, a spacecraft (and instruments) that accomplishes the same science goal by returning less science telemetry bits, has demonstrated a higher degree of autonomy. An example would be a mission that is sent to an asteroid with the science goal of determining the number of craters in different size categories and does this by downlinking hundreds of images vs. a similar mission that does on-board crater detection and size categorization and downlinks only one number for each size category - the number of craters in that category.

Like the first two autonomy metrics, Science Analysis Autonomy is scaled by the ratio of average no-track to track duration, to discourage small increases in no-track duration which result in large increases in track duration. Likewise, it is defined so that adding on-board science analysis automation that may increase no-track duration and decrease science bits downlinked, has to be weighed by its effect on ops workforce if autonomy is to be maximized.

6. SPACECRAFT MARGIN MANAGEMENT AUTONOMY

This metric addresses spacecraft designs which require a significant ops workforce to manage on-board margins and consumables. Propellant, thruster firings, tape across the head, mechanical recorder start-stop cycles, and battery charge-discharge cycles are all examples of spacecraft consumables that can require significant planning, monitoring, modeling, and bookkeeping, particularly if the design provides only minimal margins. Thermal, telecom, and power are examples of spacecraft performance capabilities that when designed with adequate margins, require little operational attention, but when designed with minimum or negative margins, can require significant operational work arounds. This metric indicates that spacecraft autonomy is inversely proportional to the number of margins and consumables that must be routinely managed by the ground and by the workforce that it takes to perform this management.

7. SPACECRAFT AUTONOMY SURVEY

Figure 1 is a survey form used to collect autonomy parameters from a variety of missions including historic missions which reported their mission autonomy metric parameter actuals, and missions yet to fly, which reported their predicted mission autonomy metric parameters . The autonomy parameters defined and entered on the data entry column of the survey form were used in the formulas given at the bottom of the survey page to compute the four autonomy metrics for each mission surveyed.

8. SPACECRAFT AUTONOMY SURVEY RESULTS

Figure 2 shows the results of the survey, with project autonomy parameter values as inputs and computed project autonomy metrics as outputs. Figure 3 is a graphic representation of the computed autonomy metrics. Collecting this data is still work in progress. As of this date (late June), Clementine and Cassini data remains to be collected. It is expected that by conference time in September, the spreadsheets will be complete.

9. WHAT AUTONOMY METRICS DON'T MEASURE- CAVEATS

The metrics defined in this paper indicate degree of spacecraft autonomy - "the ability to undertake action or carry on without outside monitor or control". High autonomy metrics

Figure 1: SPACECRAFT AUTONOMY SURVEY FORM

'reject Name:

'reject Phase:

(choose 1 phase, e.g., "cruise")

Data Submitted By: Date: **data to be entered**

AUTONOMY PARAMETERS

a • average no-track duration (hours)

b • average track duration (hours)

c • **average no-track, track cycle** duration (hours)
(should . **a + b)**

d • **average amount of data** uplinked **pet** day (bits)

e • **average amount of engineering data** downlinked per day (bits)

f • average amount **of science data** downlinked per day (bits)

g • number of spacecraft margins & consumables routinely
managed by ground

h • workforce required **for s/c** uplink (**F I E s)**

i • workforce **required for engineering** performance analysis (F**I s)**

j • workforce **required for science analysis** (FIIs)

k • workforce required **for margin &** consumables management (F **'1 Es)**

l • total operations workforce (FT **Es)**
(these parameters assume that total project ops workforce **is**
allocated between h, i, j, and k)

AUTONOMY METRICS

S/C **CONTROL AUTONOMY**
(nt dur / ul data*ul wf)(nt **dur / t** dur)
or . (a/d' tl)(a/b)

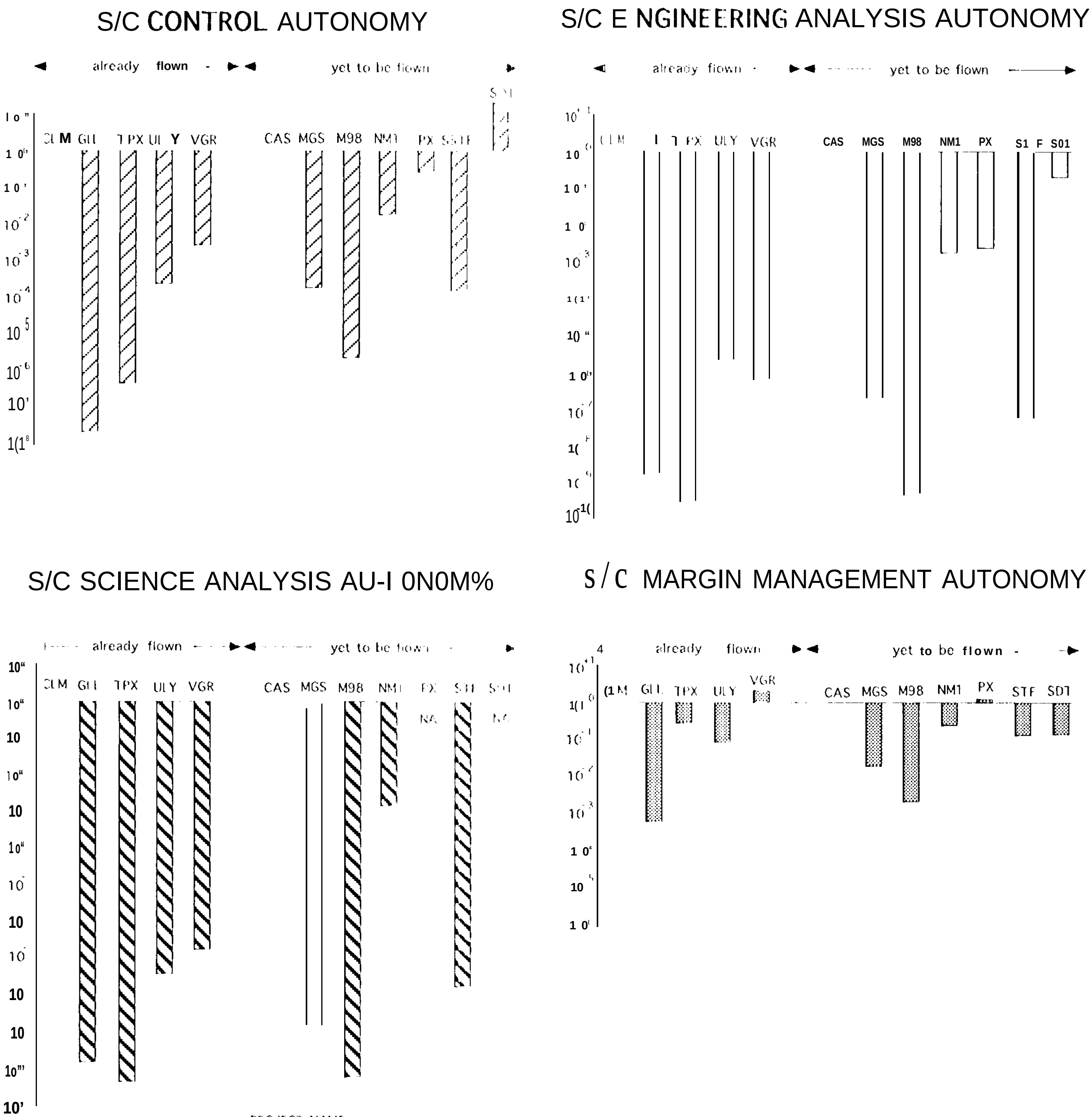
S/C SCI **ANALYSIS AUTONOMY**
(nt dur / **s** data * **sa** wf)(nt dur **/ t dur)**
or = (a/f*j)(a/b)

S/C ENG **ANALYSIS AUTONOMY**
(nt dur / **c!** data * ea wf)(nt **dur / t dur)**
or = (a/e*i)(a/b)

SK; MARGIN MNGMNT **AUTONOMY**
1/ (# margins • mm wf)
or = 1/(g*k)

	Clementine	Galileo	Topex	Ulysses	Voyager	Cassini	MGS	Mars '98	New Millennium	Pluto Express	SIRTF	Stardust
	<------------	------------	Already Flown	------------	------------>	<------------	------------	Yet To be Flown	------------	------------	------------	------------>
mission activity phase	lunar orbit	Jupiter orbit	earth orbit	polar pass	extnd msn cruise		mars orbit	relay & lander ops	cruise	beacon cruise	observatory	cruise
SPACECRAFT AUTOMATION PARAMETERS												
• average no track duration (hours)			5.75	14	8		14	4	164	23.62	11.5	164
average track duration (hours)			18.25	10	16		10	20	4	0.38	0.5	4
average no-track, track cycle (hours)			24	24	24		24	24	168	24	12	168
• av data uplink per day (bits)			[illegible]	10,000	123		10,000	10,000	286,000	533	226,000	43
av eng data return per day (bits)			[illegible]	2.0E+08	[illegible]		2.2E+07	[illegible]	[illegible]	[illegible]	4.8E+08	[illegible]
• av science data return per day (bits)			[illegible]	[illegible]	6.6E+06		9.7E+08	4.5E+08	[illegible]	NA	[illegible]	NA
# s/c margins & cons routinely managed			3	2	1		[illegible]	[illegible]	[illegible]			
• workforce required for s/c uplink			25.8	[illegible]	6.8		10.1	22	2	5.5	9	4
• workforce required for eng analysis			9.2	4	7.7		5.3	8	3	4.5	7	2
workforce for sci			26.7	5.5	2.6		15.5	20	1	NA	6	NA
• workforce reqd for margin mngmnt			0.8	[illegible]	0.3		4.2	[illegible]		0.5	[illegible]	2
(checksum: = total ops workforce)			62.5	19.7	17.4		35	72	7	10.5	25	8
SPACECRAFT AUTONOMY METRICS												
S/C CONTROL AUTONOMY (nt dur / ul data*ul wf)(nt dur + t dur)		3.5E-08	7.5E-07	3.9E-04	4.8E-03		1.9E-04	3.6E-06	1.2E-02	5.0E-01	1.3E-04	3.9E+01
S/C ENG ANALYSIS AUTONOMY (nt dur / e data * ea wf)(nt dur / t dur)		[illegible]5E-03	5.2E-10	2.5E-06	9.0E-07		.7E-07	7.4E-10	1.6E-03	3.4E-03	8.7E-08	1.6E-01
S/C SCI ANALYSIS AUTONOMY (nt dur / s data * sa wf)(nt dur / t dur)		.4E-10	6.8E-11	5.7E-08	1.8E-07		1.9E-09	8.9E-11	1.2E-03	NA	1.3E-08	NA
S/C MARGIN MNGMNT AUTONOMY ([illegible] / # mrgns * mm wf)		8.3E-04	4.2E-01	9.6E-02	3.3E+00		1.5E-02	2.6E-03	5.0E-01	.0E+00	1.1E-01	1.3E-01

FIGURE 3: CHART OF SPACECRAFT AUTONOMY METRICS 6/11/96



PROJECT NAME ABBREVIATIONS KEY:

CAS = CASSINI
CLM = CLEMENTINE
GLL = GALILEO
MGS = MARS GLOBAL SURVEYOR
M98 = MARS '98
NM1 = NEW MILLENNIUM FL1
PX = PLUTO EXPRESS
STF = SIRTF
SDT = STARDUST
TPX = TOPEX
ULY = ULYSSES
VGR = VOYAGER

reflect a spacecraft's ability to operate for long periods of time with minimum ground contact (tracking), with a small operations workforce, and with a small amount of data interchange between itself and the ground.

Below is a list of some of the things that Spacecraft Autonomy Metrics do not measure:

1- Risk - missions willing to take more risk can generally improve their autonomy metrics by reducing tracking, down staffing, and sending and receiving less data. The autonomy metrics do not measure risk.

2- Cost Effectiveness - projects can spend significant funds pre-launch, developing and testing spacecraft autonomy. The autonomy metrics do not indicate whether reduced ops costs (due to the autonomy) will offset higher development costs and result in a net life-cycle cost savings.

3- The Value of Engineering Data - over and above risk reduction, engineering data can have intrinsic value, especially for missions with technology evaluation goals. The autonomy metrics indicate that the more engineering data required to be routinely downlinked, the lower the spacecraft autonomy. The autonomy metrics do not try and assess the "value" of engineering data downlinked.

4- The Value of Science Data - the purpose of most NASA missions is to go out into space and collect science information. Returning this information usually requires downlinking science data. The autonomy metrics indicate that the more science data required to be routinely downlinked, the lower the spacecraft autonomy. The autonomy metrics do not try and assess the "value" of the science data downlinked.

5- Ground Automation - missions can exploit ground automation to reduce ops workforce and this results in an improved spacecraft autonomy metric. The spacecraft autonomy metrics do not try and asses the degree of ground system automation.

6 - Mission Complexity - very simple missions, like probes, can achieve significantly high levels of spacecraft automation. Projects in general can improve spacecraft autonomy metries by simplifying their mission design. The autonomy metrics do not try and asses the complexity of mission design.

10. SUMMARY

Four spacecraft autonomy metrics have been proposed that attempt to quantify the degree of outside control required for a spacecraft to perform and meet its mission goals. The duration the spacecraft can operate between tracks, the amount of data that must be exchanged between the spacecraft and the ground, and the size of the operations workforce are some of the parameters that influence the proposed autonomy metrics.

A variety of missions were surveyed and their autonomy metrics computed. Significant differences (orders of magnitude) were discovered between the autonomy of missions which have flown (autonomy actuals) vs. some missions which have yet to fly (autonomy predicts). These significant differences could be due to new project naiveté (not yet fully understanding mission operational complexity), new project buy-in (assuming optimistic tracking and ops cost estimates to help sell the project), or anticipated use of highly effective new spacecraft automation technology. It is expected that these autonomy metrics will start being used in the future to set measurable autonomy goals for future projects, to compare benefits between competing automation technologies, and to develop an understanding of the relationship between a project's pre-launch autonomy performance predicts and its post-launch autonomy performance actuals.